Stability of the Accretion Flows with Stalled Shocks in Core-Collapse Supernovae

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References : Y&Y, ApJ 650,291 (2006)
Y&Y, ApJ 656,1019 (2007)

§ Introduction

- Observations suggest that the explosions are asymmetry (polarization, pulsar kick, images of 1987A).
- Multi dimensional simulations indicate that the accretion flows in SNe are unstable against asymmetric pertrubations.

→ Hydrodynamical instability is one of the key ingredients of asymmetry (and possibly explosion).

Known instability mechanisms :

convection,

advection-acoustic cycle (Foglizzo 2000, 2001, 2002),

….

§ This study

We investigated the stability systematically.

1. First, we found steady solutions which mimic the accretion flow with a stalled shock in the core-collapse supernovae, assuming that the neutrino luminosity and the mass accretion rate are constant parameters.
2. Then the stability of the steady solutions was investigated by global analysis.

★ The realistic equation of state by Shen is employed.

★ We took into accout both neutrino heating and cooling, adopting the realistic reaction rates by Bruenn (1985).

§ Assumptions

We consider the region between shock and neutrino-sphere.

1. Steady flows are spherically symmetric.
2. Neutrino thin approximation is adopted (*i.e.*, neutrino transfer is not solved).
3. Newtonian gravity is adopted.

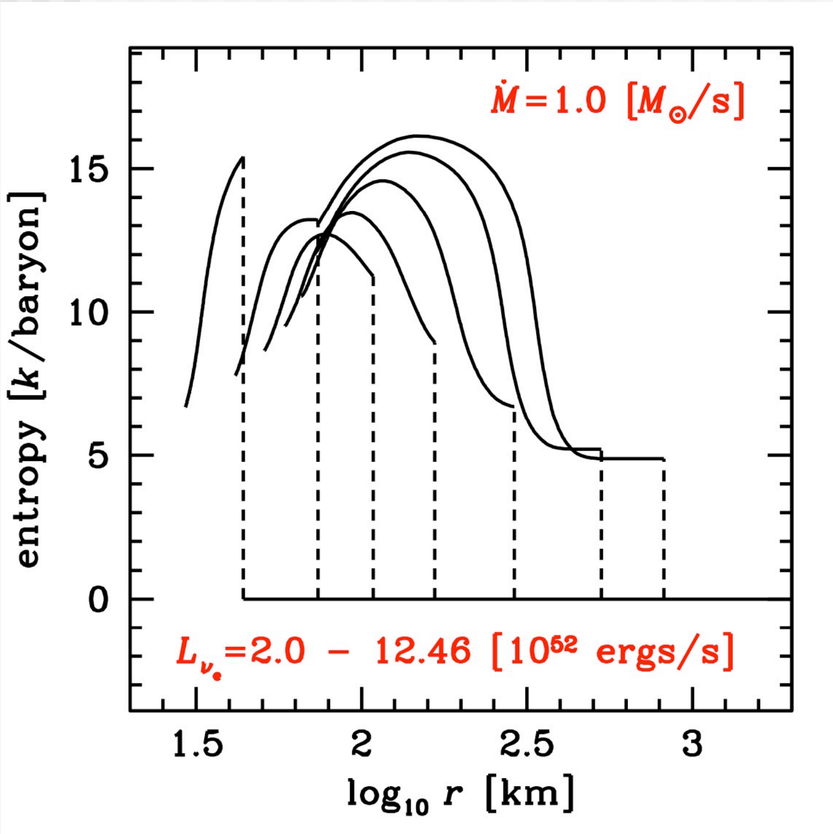
Boundary conditions

a) Flow outside of the shock is cold free-fall one.

b) At the inner boundary (neutrino-sphere), the perturbation of the radial velocity vanishes.

➔ Perturbations are expanded in the spherical harmonics, and radial dependence of the perturbations are solved globally.

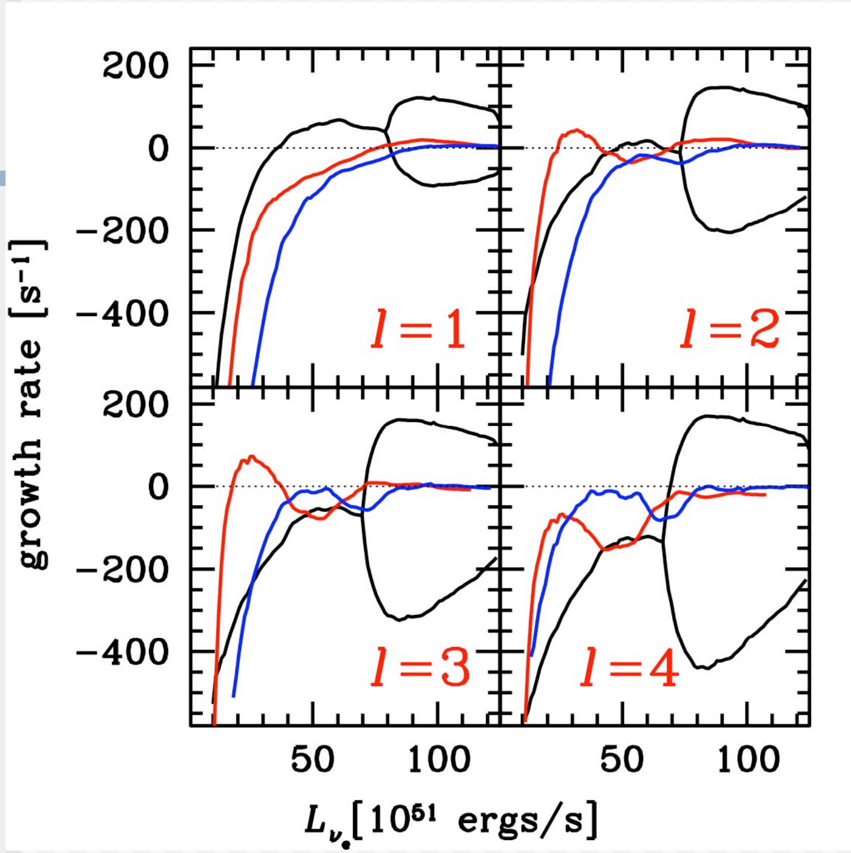
§ Steady solutions

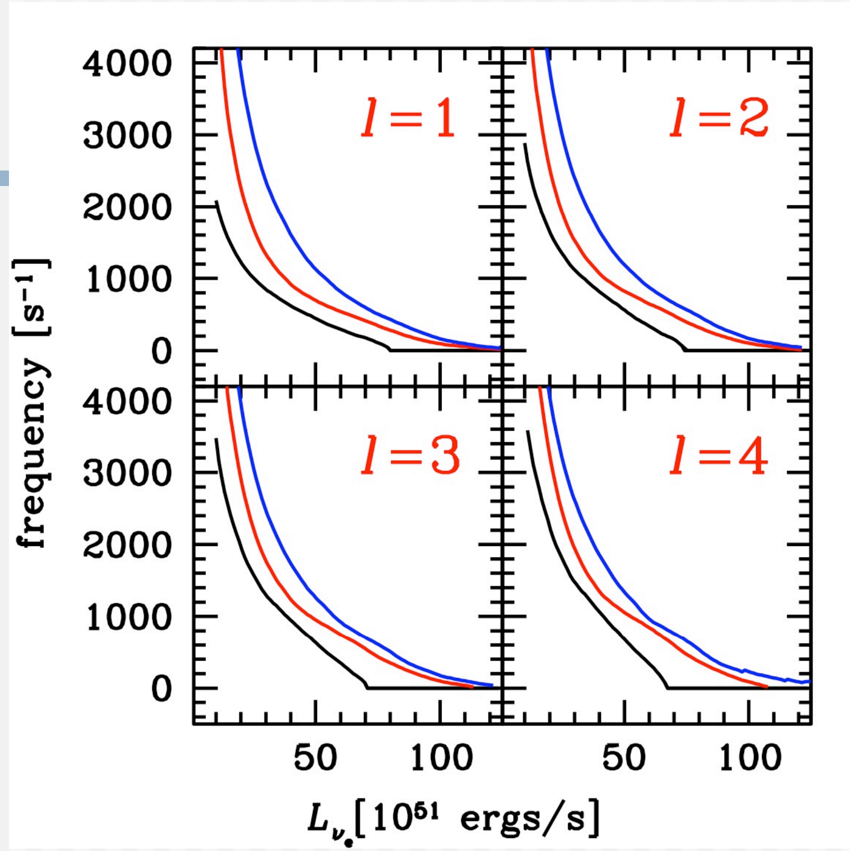


- When the neutrino luminosity exceeds the critical value ($12.46 \cdot 10^{52}$[ergs/s], for accretion rate 1.0 [$M_\odot$/s]), there exist no steady solutions (Burrows & Goshy 1993).

- When the neutrino luminosity is larger than about $4.0 \cdot 10^{52}$[ergs/s] (for accretion rate 1.0 [$M_\odot$/s]), there is the heating layer where the entropy gradient is negative in the radial direction.

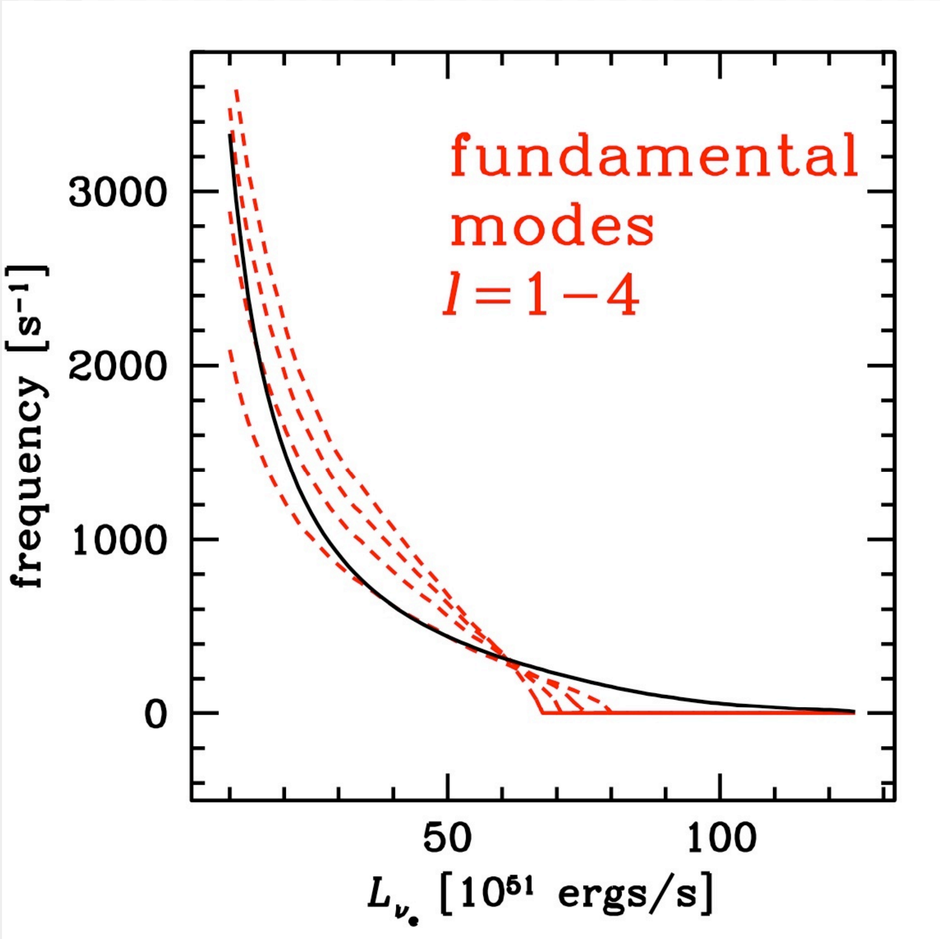
§ Results *growth rates and frequencies*





1. $L_\nu < 1 \cdot 10^{52}$[ergs/s] No unstable mode.
2. $2 < L_\nu < 4 \cdot 10^{52}$[ergs/s] l=2,3 oscillatory modes grow (advection-acoustic).
3. $3 < L_\nu < 7 \cdot 10^{52}$[ergs/s] l=1,2 oscillatory modes grow (advection-acoustic).
4. $L_\nu > 7 \cdot 10^{52}$[ergs/s] Non-oscillatory modes grow (convection).
   l=5 -11 grows fastest (*c.f.* Foglizzo et al. 2006).

Frequencies for oscillatory modes

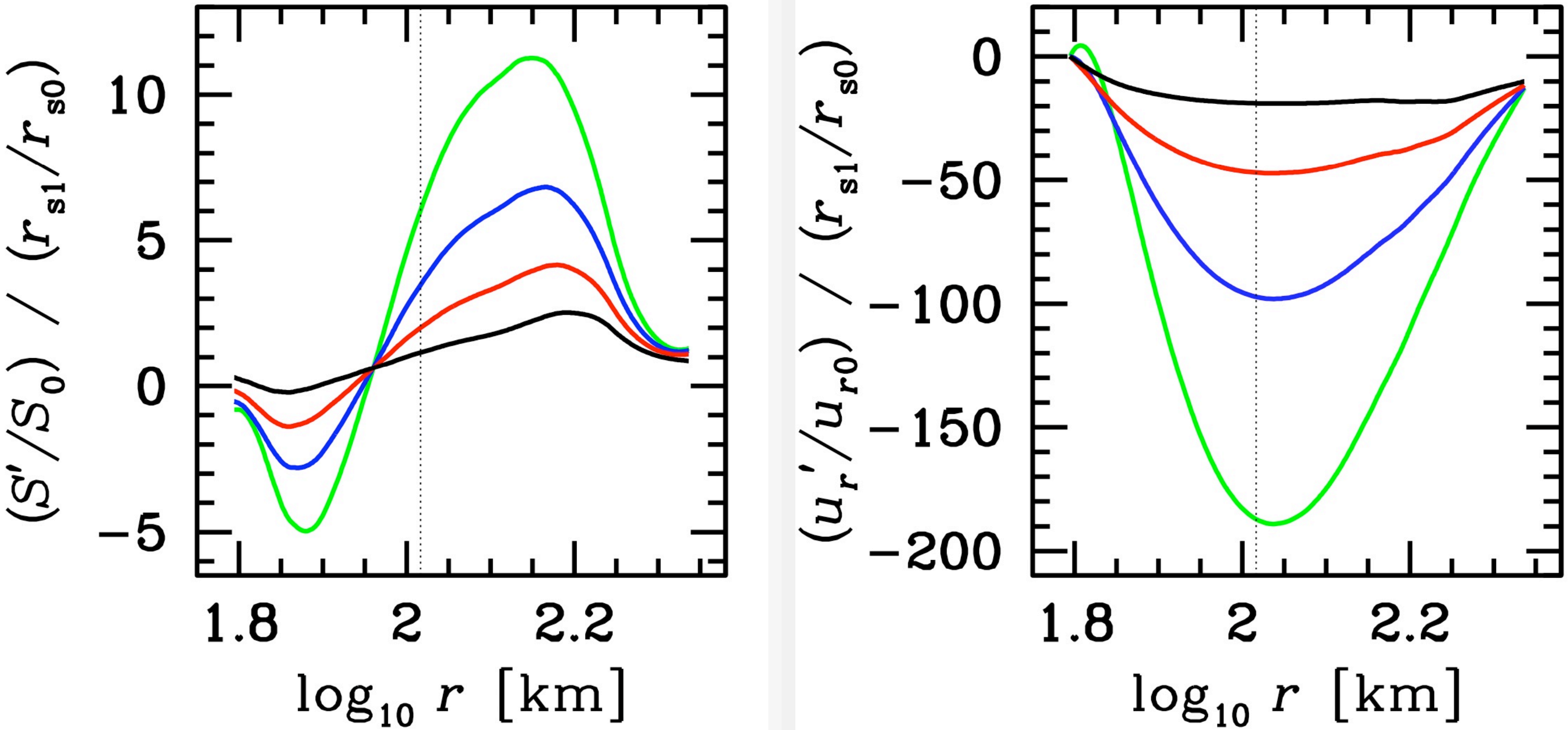


- Frequencies are consistent with those predicted by the advection-acoustic cycle.

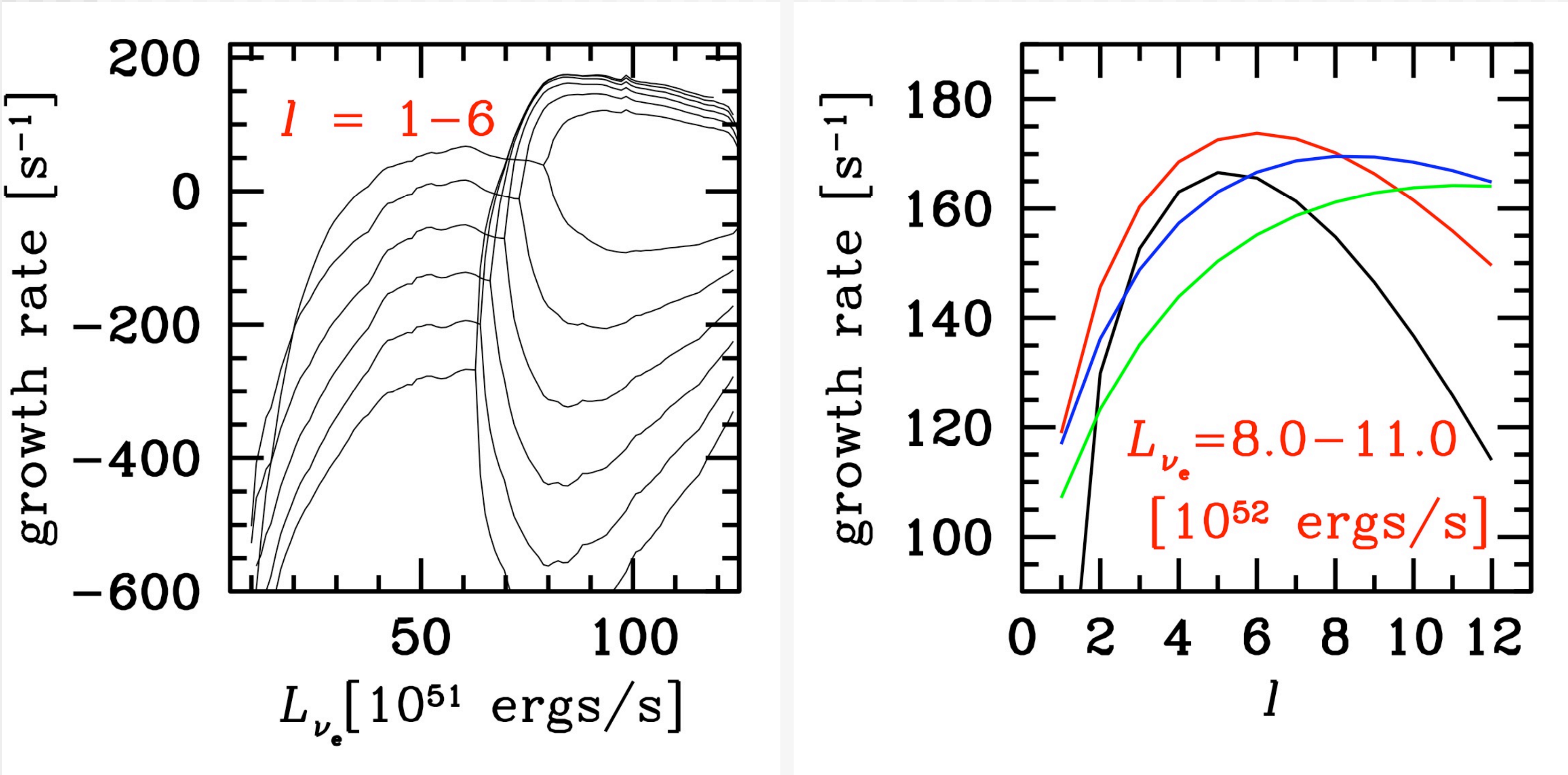
→ The oscillatory modes are likely to be the advection-acoustic cycle (Foglizzo et al. 2007).

★ The stability of the oscillatory modes are affected quantitatively by the inner boundary condition (whereas non-oscillatory modes are not).

Eigen-functions of non-oscillatory modes



Growth rates for convective modes



§ Summary

For mass accretion rate 1.0 [$M_\odot$/s],

1) $L_\nu > 12.46 \cdot 10^{52}$[ergs/s] No steady solutions.
2) $L_\nu > 4 \cdot 10^{52}$[ergs/s] Heating region emerges.

1. $L_\nu < 1 \cdot 10^{52}$[ergs/s] No unstable mode.
2. $2 < L_\nu < 4 \cdot 10^{52}$[ergs/s] l=2,3 advection-acoustic modes grow.
3. $3 < L_\nu < 7 \cdot 10^{52}$[ergs/s] l=1,2 advection-acoustic modes grow.
4. $L_\nu > 7 \cdot 10^{52}$[ergs/s] Convective modes grow (l=5-11 grow fastest).

★ Even when the radial gradient of entropy is negative, the convection does not always take place because of the advection (Foglizzo et al. '06).

★ The advection-acoustic cycle and the convection become important in different aspects.